

National Renewable Energy Laboratory
Wind Turbine Condition Monitoring Workshop

Synchronous Sampling in Wind Turbine Gearbox Condition Monitoring

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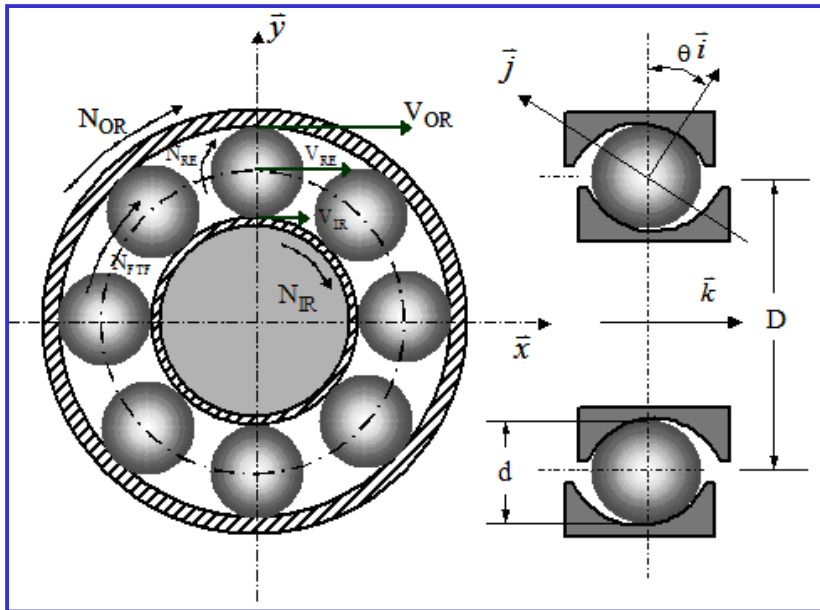
October 8 - 9, 2009

Broomfield, CO

Outline

- Background
- Motivation
- Synchronous Sampling
- Synthesized Synchronous Sampling
- Numerical Simulations
- Test Rig Application
- Summary

Background



$$f_{FTF} = \frac{1}{120} \left[N_{OR} \left(1 + \frac{d}{D} \cos \theta \right) + N_{IR} \left(1 - \frac{d}{D} \cos \theta \right) \right]$$

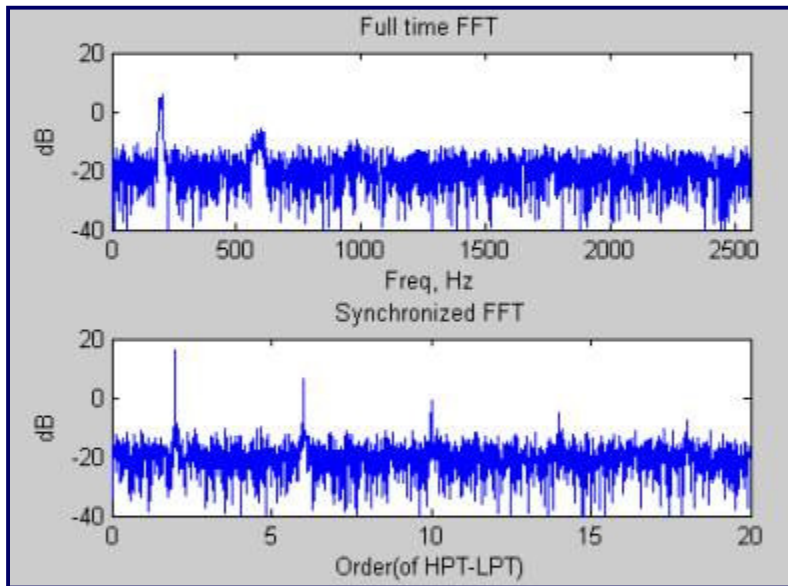
$$f_{RE} = \frac{D}{120d} \left(1 - \frac{d}{D} \cos \theta \right) \left(1 + \frac{d}{D} \cos \theta \right) |N_{OR} - N_{IR}|$$

$$f_{BPFI} = \frac{n}{120} \left(1 + \frac{d}{D} \cos \theta \right) |N_{OR} - N_{IR}|$$

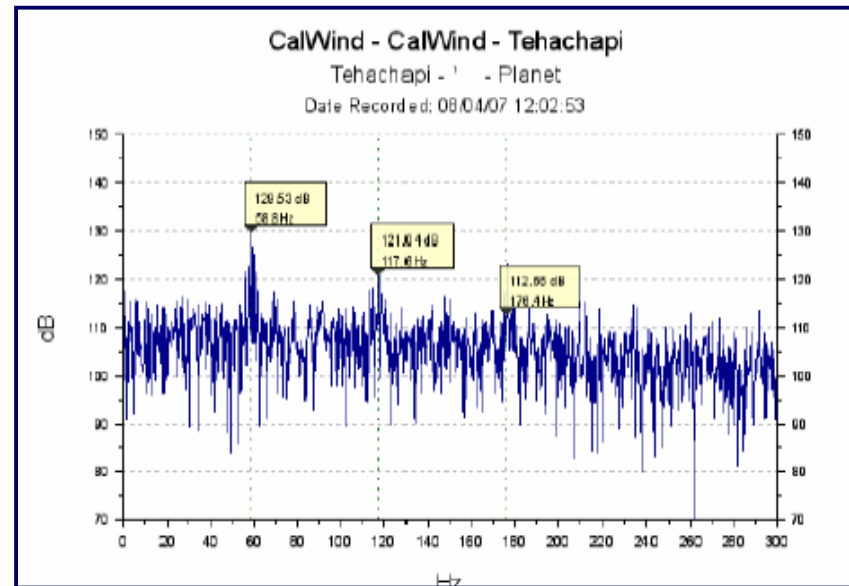
$$f_{BPFO} = \frac{n}{120} \left(1 - \frac{d}{D} \cos \theta \right) |N_{OR} - N_{IR}|$$

Differential bearing signatures are function of the speed difference

Background



Simulated Variable Speed Turbine Vibration



Real Wind Turbine Vibration*

In FFT analysis a signature can be buried and the signature amplitude can vary due to speed variations

Motivation

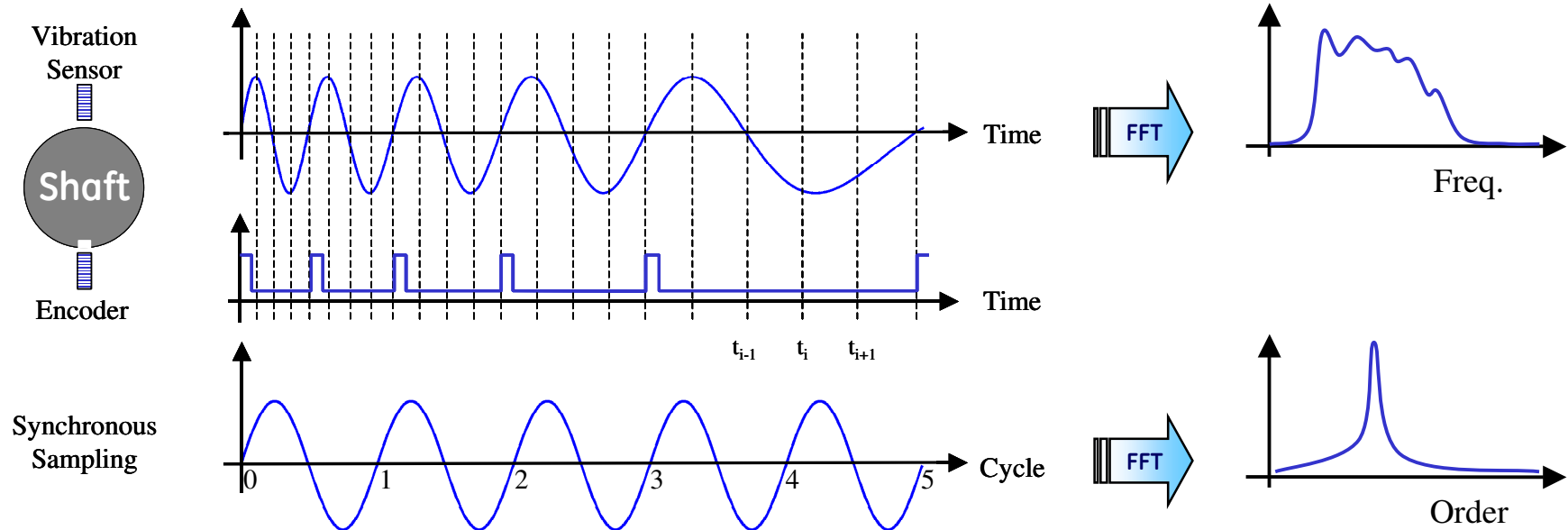
? How to enhance the differential bearing (gear) damage features if

- Speed of shaft(s) are not well controlled
- Encoders from one or both races are not available, but the speed profiles are available

⇒ Synthesized Synchronous Sampling

How to do synchronous sampling without encoders?

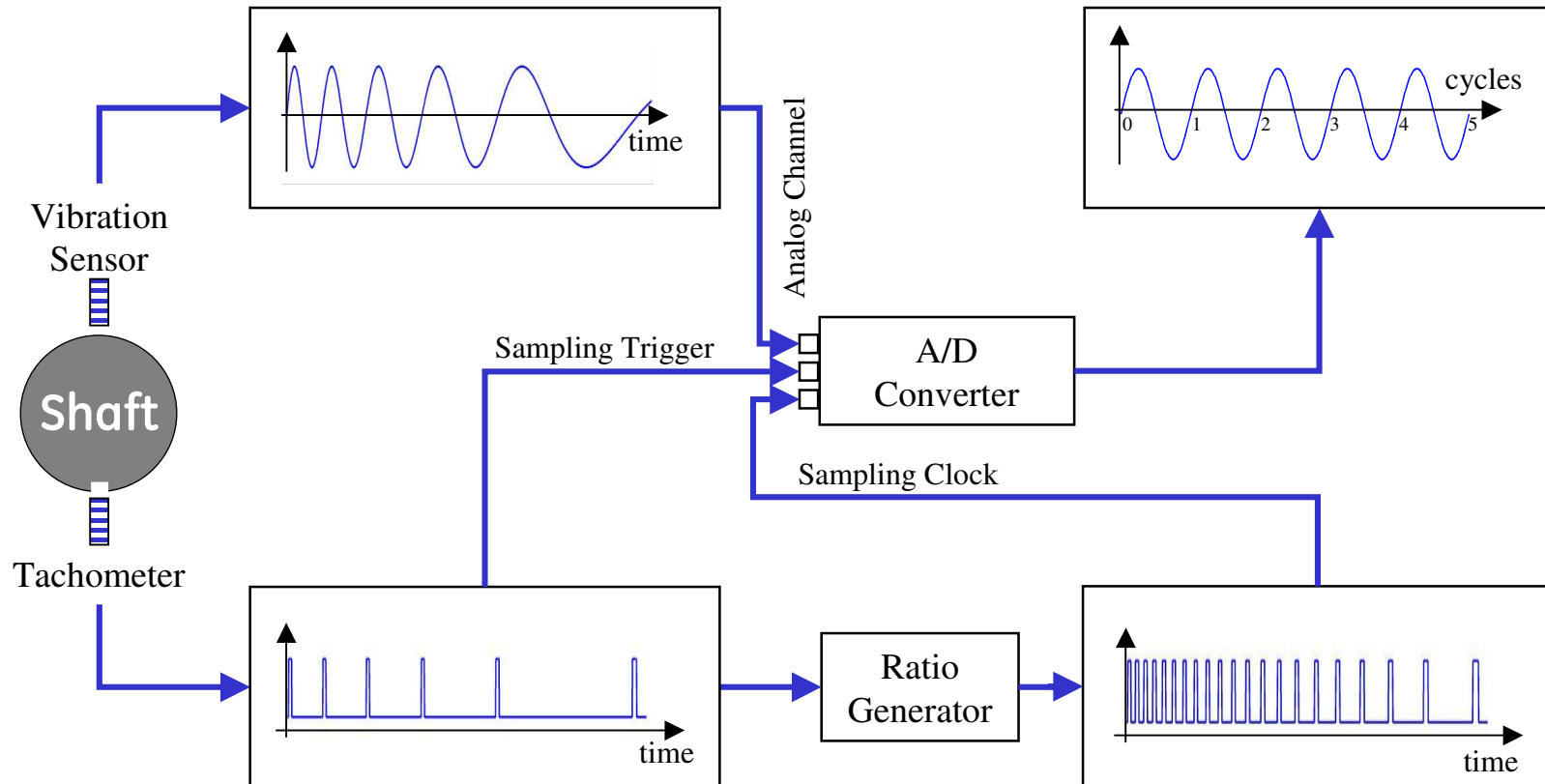
Synchronous Sampling



Synchronous Sampling Guarantees Full Cycle Sampling

Encoder is the key in conventional synchronous sampling

Synchronous Sampling



A way of synchronous sampling realization

Synthesized Synchronous Sampling

Basic Steps:

- Assume a pulse at time zero;
- Once the i^{th} pulse is located, at t_i , assume the $(i+1)^{th}$ pulse be located at t_{i+1} ;
- Calculate the average shaft speed, n in PRM, from t_i to t_{i+1} .

$$n(t_{i+1}) = \frac{1}{t_{i+1} - t_i} \int_{t_i}^{t_{i+1}} \text{ShaftSpeed}(t) dt$$

- Formulate the time elapsed from t_i to t_{i+1} .

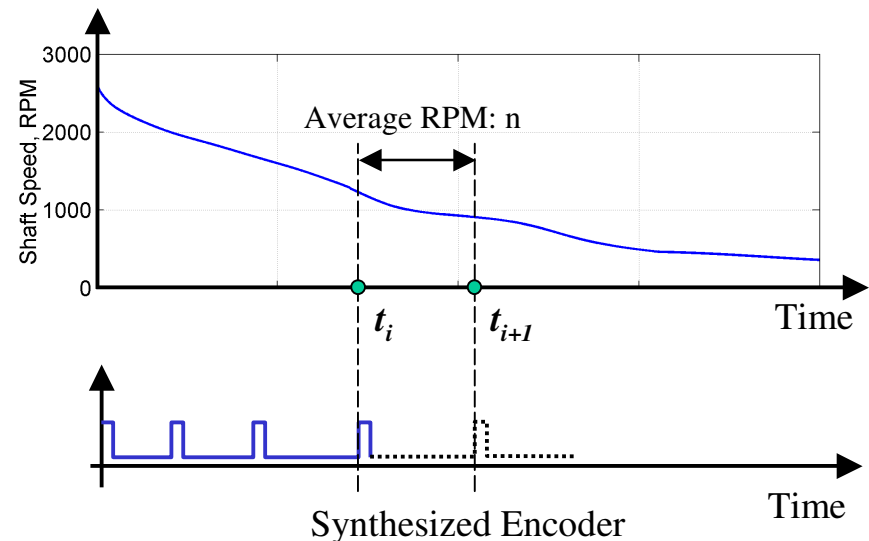
$$\Delta t_1 = t_{i+1} - t_i$$

- The time elapsed by one instantaneous rotation

$$\Delta t_2 = 60 / n$$

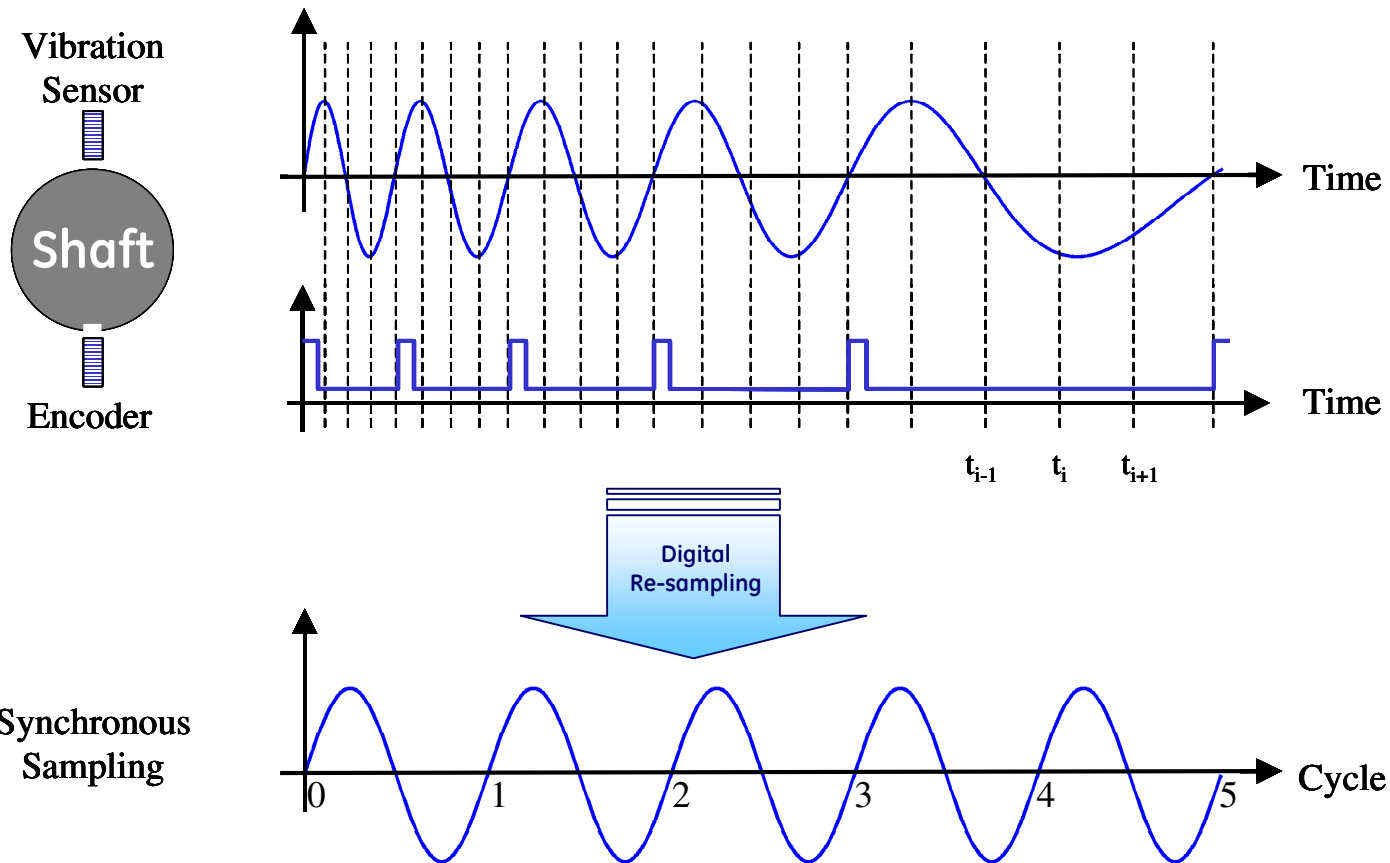
- Solve t_{i+1} in the following minimization.

$$\min_{t > t_i} |\Delta t_1 - \Delta t_2|$$



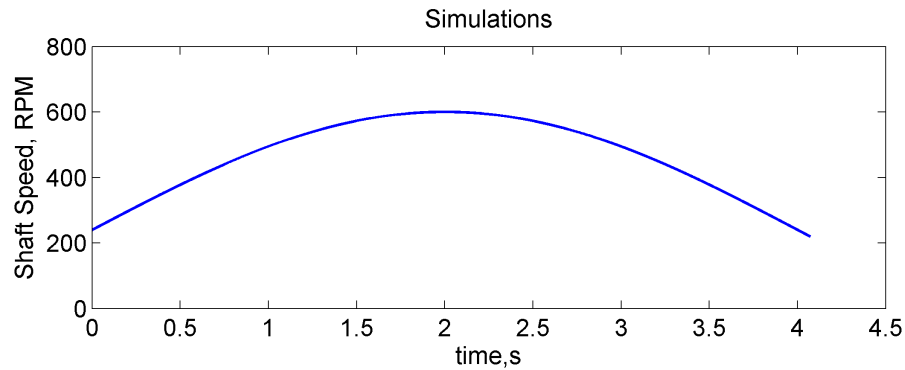
A Mathematically Simple and Easy to Implement Approach

Synchronous Sampling

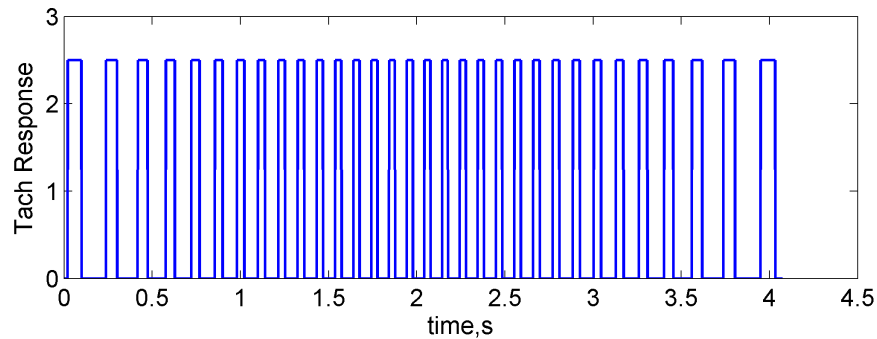


Synchronous Sampling in Digital Domain with Synchrophaser
- No Limitation in Synchronous Re-sampling

Simulations



Simulated Shaft Speed



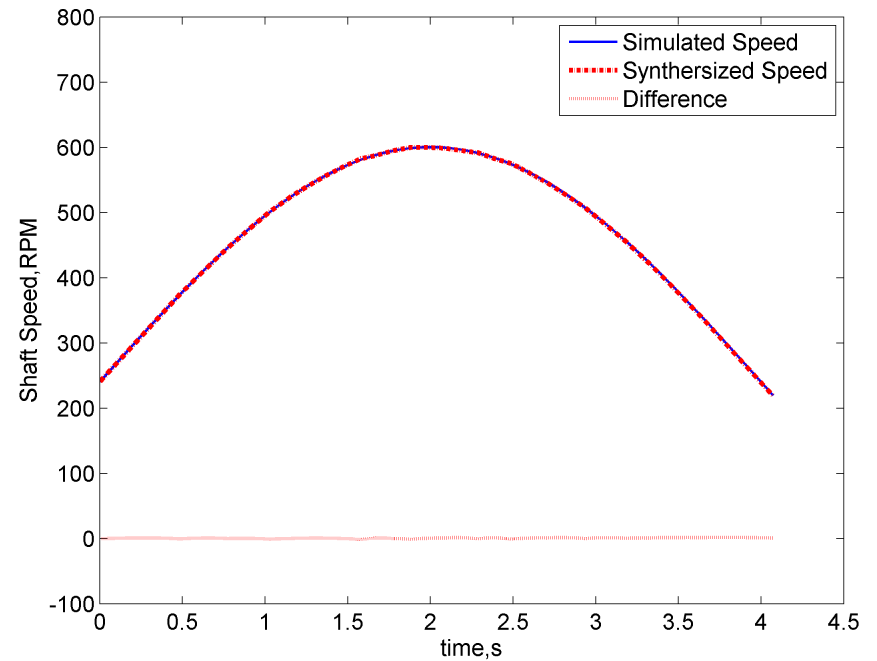
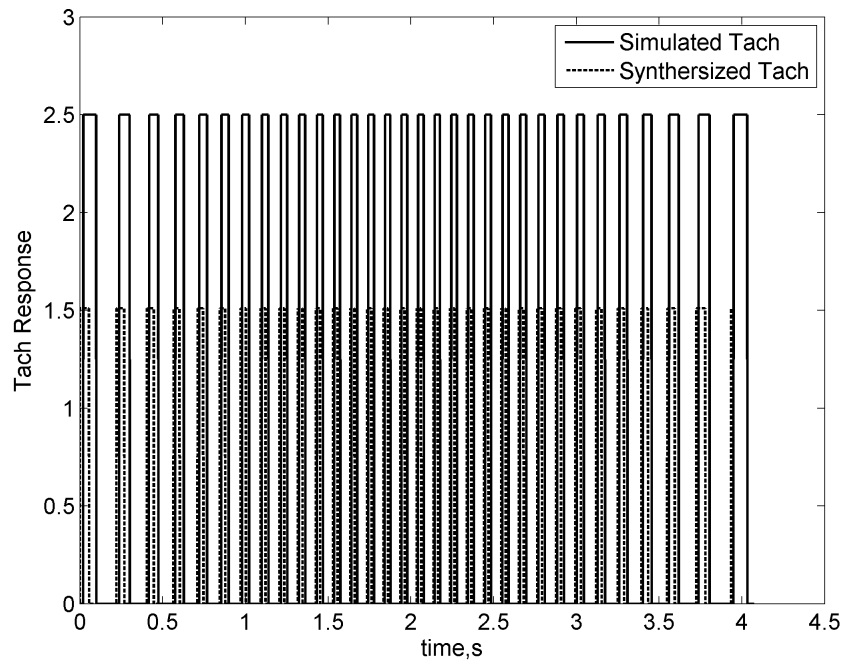
Simulated Synchrophaser

Variable Shaft Speed Simulation



imagination at work

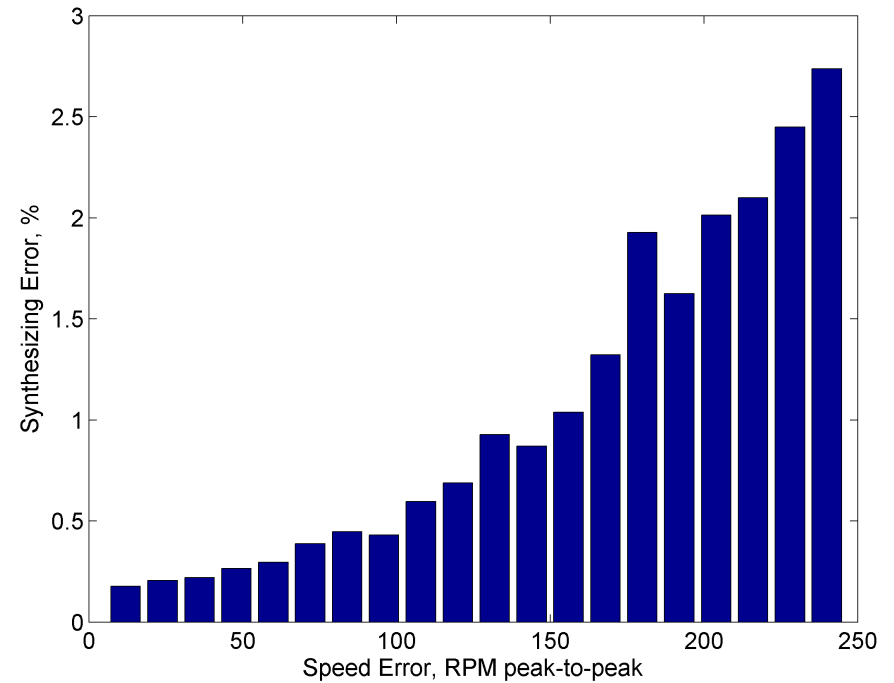
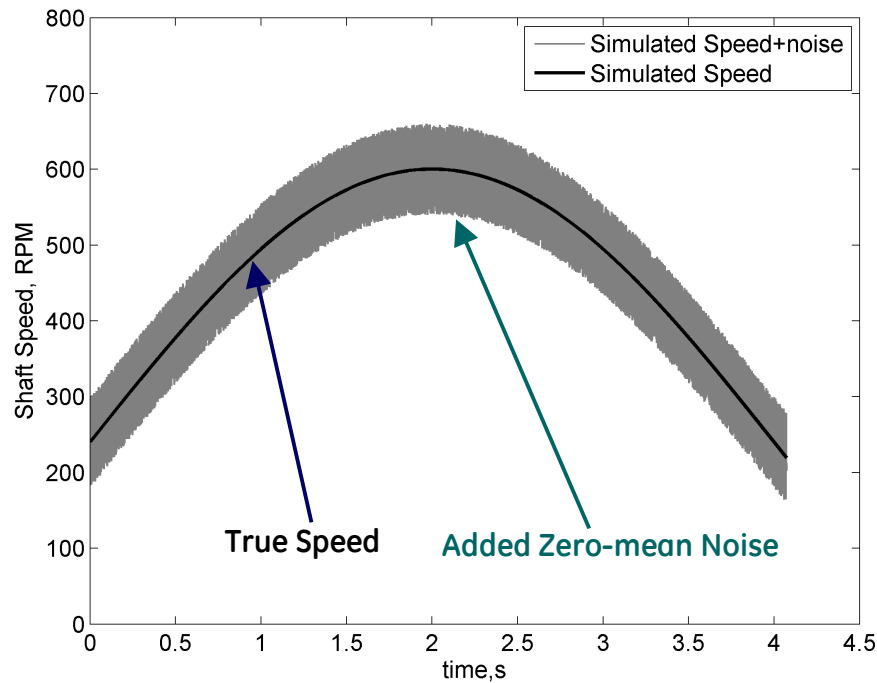
Simulations



$$Error \equiv \sqrt{\frac{(n_{Simulated} - n_{Synthesized})^T \cdot (n_{Simulated} - n_{Synthesized})}{n_{Simulated}^T \cdot n_{Simulated}}} \times 100\% = 0.2\%$$

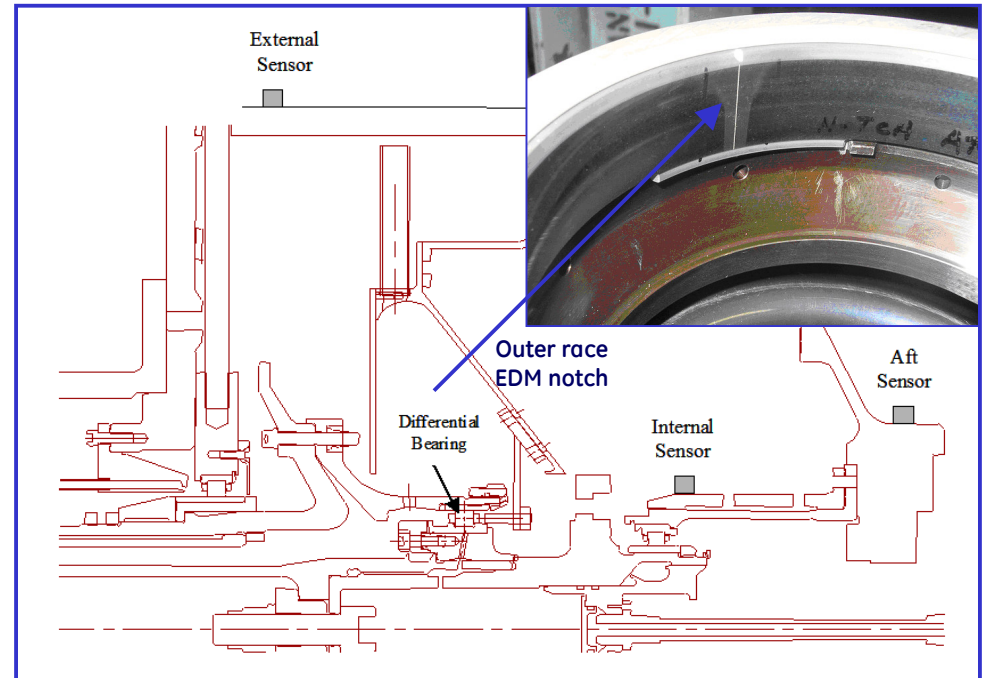
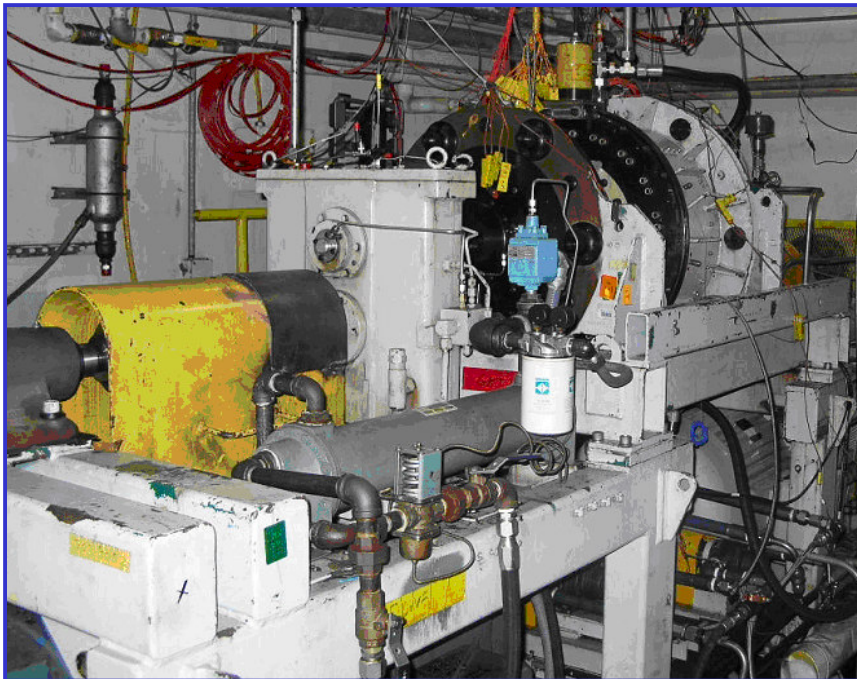
Synthesized Encoder and Speed – Accurate

Simulations



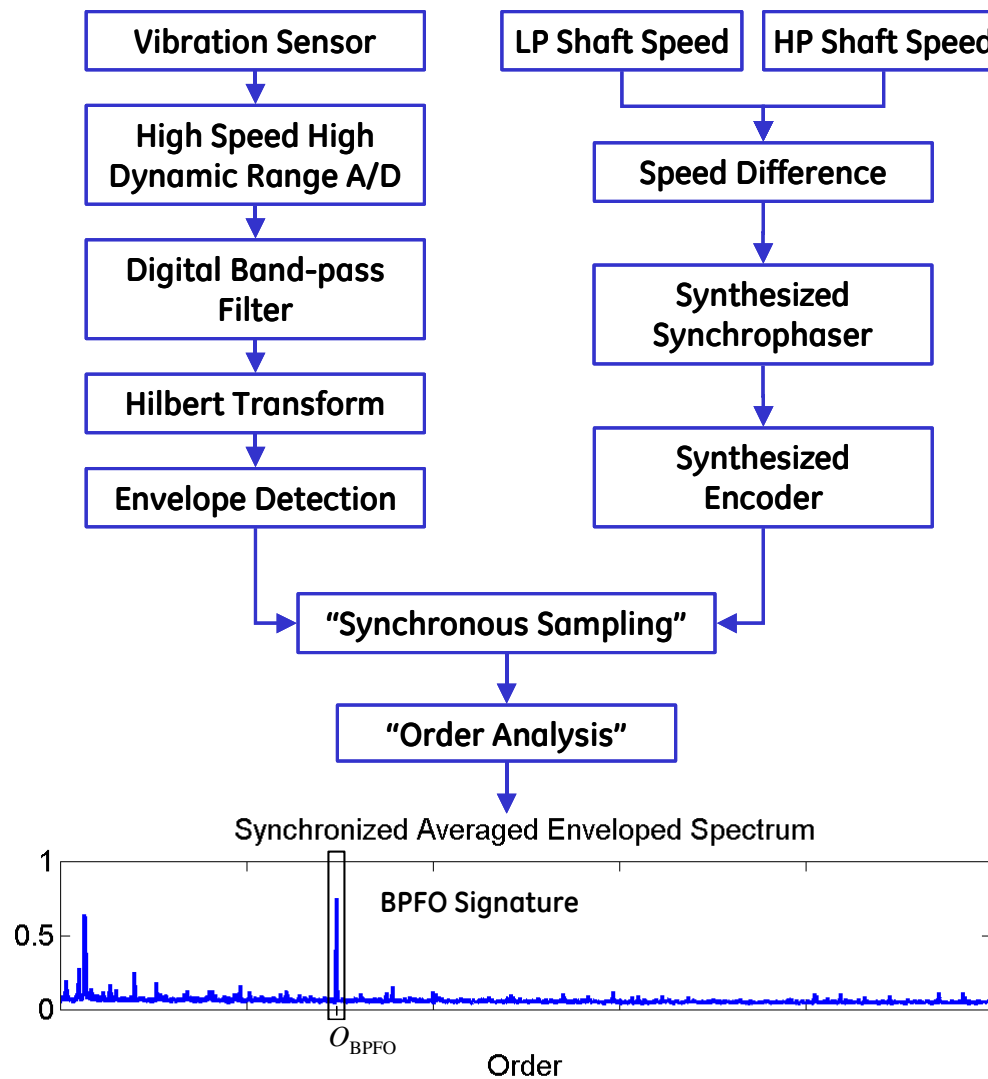
Synthesized Encoder and Speed – Accurate and Robust with Noise

Engine Application



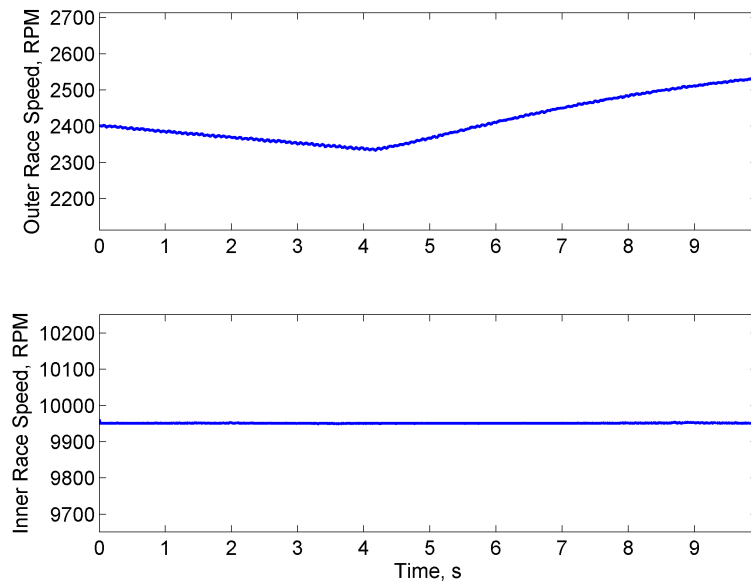
Differential Bearing Test Rig with Outer Race Defect

Engine Application

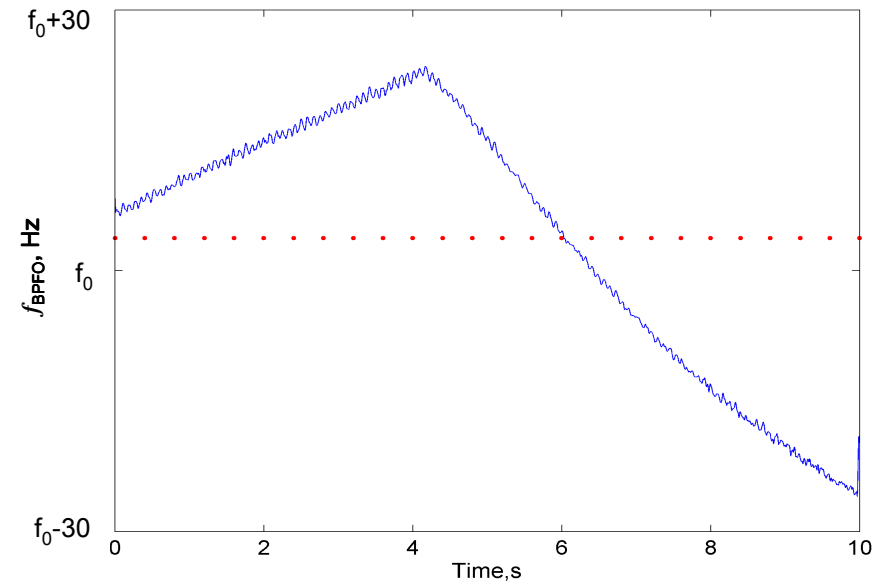


Engine Application

Shaft Speeds

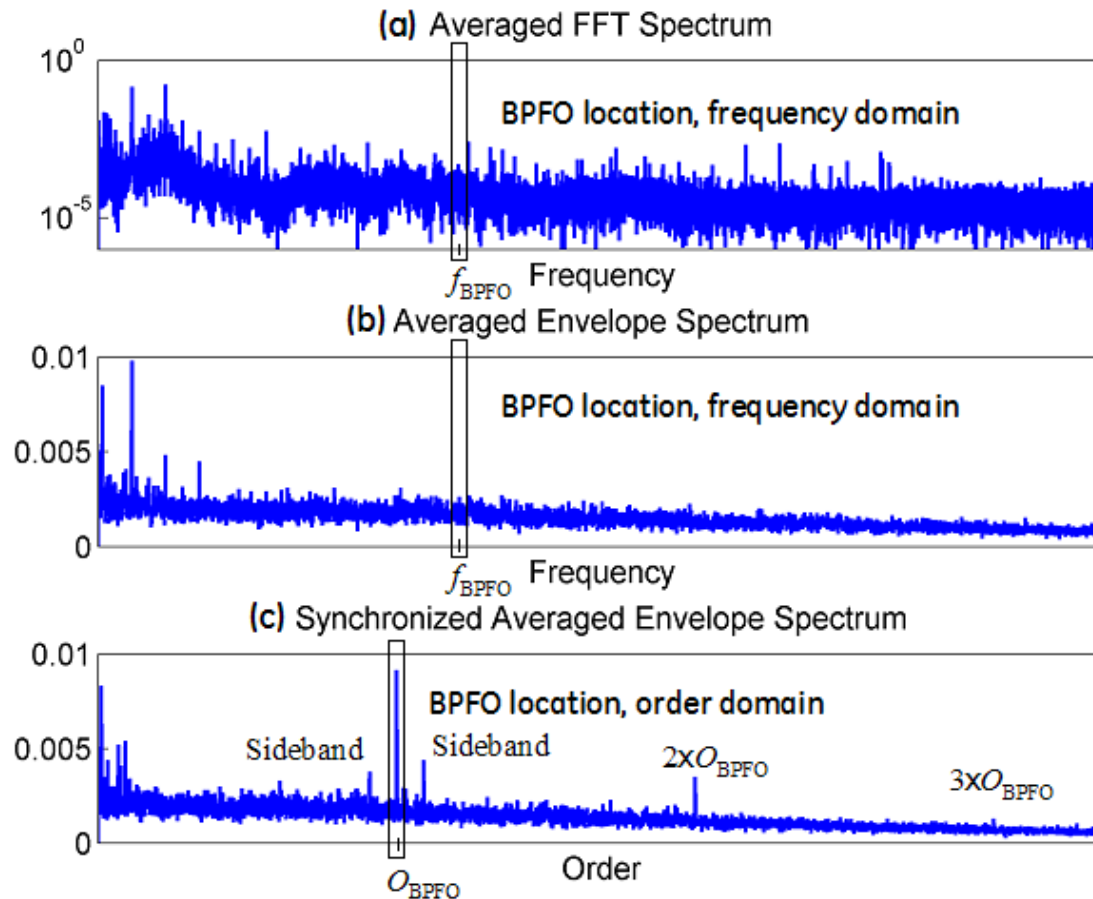


BPFO



Shaft Speed Variations => Bearing Signature Variations

Engine Application



Significant Improvement using Synthesized Synchronous Sampling



imagination at work

Summary

- Developed a synthesized synchronous sampling (SSS) technique from a speed profile;
- Numerical simulations verified the accuracy of the SSS technique;
- Engine test rig data analysis results indicate the effectiveness of extracting differential bearing damage features in variable speed operations;
- Initial wind turbine production test stand data analysis results shown the SSS is very promising.

Thanks!